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Mr. Robert W. Henry
National Transportation Safety Board
Office of Marine Safety (MS30)
490 L'Enfant Plaza East, S.W.
Washington, D.C 20594

Attention: Mr. R. W. Henry

Subject: Investigation into the Electrical Fire on the M/V Columbia on 6 June 2000

JHU/APL was tasked to investigate the origin and cause of an electrical fire in the main switchboards of the M/V Columbia. After examining the ship and talking to the crew it has been determined to a high degree of engineering confidence that the fire originated on the supply side bus of breaker P456. The most likely cause of the fire was a stray bolt that was later found on the back of a support angle in the lower front of switchboard section 12. This report will focus on how these conclusions were derived and will not go into details of events after the fire.

Background:

On 13 June JHU/APL was contacted by Mr. Robert Henry of NTSB and informed that there had been what appeared to be an electrical fire on the M/V Columbia. Mr. Don Strawser of NAVSEA had suggested that JHU/APL might be able to assist in determining the origin and possible cause of the fire. A statement of work was drawn up tasking JHU/APL to provide a report concerning the origin and cause of the fire and a contract was set in place. Mr. H. Bruce Land of JHU/APL arrived in Ketchikan, Alaska and met Mr. Tom Roth-Roffy of NTSB at the Alaska Ship and Drydock, Inc. (ASD) facility at 8:00 AM on 16 June. The ship was still under tow and did not arrive from the Auke Bay Terminal until late that evening. The intervening time presented a good opportunity to interview Mr. Roth-Roffy of NTSB and Mr. Dave Reichl of the Alaska Marine Highway System concerning their investigations of the incident. Mr. Reichl supplied a good selection of annotated photographs for study.

The M/V Columbia is owned and operated by the Alaska Marine Highway System. At 418 feet, it is the largest and fastest vessel of the Marine Highway fleet and has a capacity of 625 passengers and 134 vehicles. It has 91 cabins and caries a crew of over 60 people. The press release stated that a minor fire occurred in the main switchboard of the control room and was safely extinguished, Attachment 1. Propulsion power was lost. The passengers were all safely evacuated to the M/V Taku and the ship was towed to the Auke Bay ferry terminal in Juneau. The Ketchikan Daily News reported that repairs would cost between $500,000 and $1 million and take the rest of the summer. The gross revenue for June through September 1998 was $7.3 million.

Mr. Alan Lee, Chief Engineer of the ship, related that cleaning and inspection of the switchboards was last performed in 1995. Maintenance was scheduled to occur in the switchboards in 1998, but was skipped due to the other more pressing needs. Mr. Lee reported that some modifications were performed on the switchboard this past spring, but he was not aware that anyone had opened the switchboards since then.

The ship was laid up early last November and returned to the water 24 May 2000. In February ASD had begun reworking breaker P412. An additional T-200 cable was pulled from the switchboard to a remote load center power panel, P2, to allow for additional power in the remote panel. When ASD went to attach the cable to the load side of the breakers, they found that they were short the three cable lugs needed. Attached to the spare breaker on the opposite end of the row were a cable and three lugs. The spare cable was removed from the breaker and secured with nylon cable ties. The lugs were moved to the new cable and attached to breaker P412. P412 was upgraded from 200 A to 400 A. This work did not require changing the breaker base. Work in the switchboard ended approximately 17 April.

The Event:

On Tuesday, June 6, 2000 at approximately 12:07 PM a fire occurred in the main electrical switchboards of the M/V Columbia. Mr. Lee Chapman, oiler on watch, was sitting about 20 feet from the end of the switchboard where the fire first occurred, with his back to the fire. He was talking to the Jr. Engineer, Mr. Tom Wood, who was sitting to his right and was facing the switchboard. Suddenly, there was a bright flash from Section 12 at the far end of the switchboard.. This was followed by a low noise described as a roar. Almost immediately, fire came out of Section 10 and flames rolled along the overhead. As the room filled with smoke, Mr. Chapman and Mr. Woods left through the port door on the side of the room opposite from the fire. Mr. Chapman reported that nothing unusual happened before the fire.

Soon after the start of the fire, the number two generator was seen to be hopping wildly. Personal recollections of the amount of time that elapsed during high stress events is subjective and error prone. Based upon recollections and reenactments, it is believed that the number two generator was shut down 30-45 seconds after the initiation of the fire. The number one generator then began hopping for another 15-30 seconds before it quieted down on its own.

Mr. Glen Scott, First Assistant Engineer, was in the crew's mess at the time the lights started to flicker. He checked that the emergency generator was working, and then went below to assist. After donning breathing equipment, SCBA, he entered the control room to attempt to open the bus-tie breaker to the emergency board. Using the butt of his flashlight, he opened the bus-tie breaker and one other breaker. Upon attempting to open the third breaker, he saw a large blue arc and decided to exit the control room.

The lights were reported by several people to have flickered several times over a period of several minutes immediately after the initiation of the fire. This tends to indicate that the ABT (automatic bus transfer switch) was switching back and forth between emergency power and main power. Several CO_2 extinguishers were discharged into the fire without completely extinguishing the fire. At some point, Coast Guard firefighters arrived and continued the fire fighting until all was under control. After the fire, both generator breakers were found in the tripped position, but it is not known when they tripped or what caused them to trip. The field notes of Ms. N. McAtee and Mr. T. Roth-Roffy contain the detailed minutes of the interviews they conducted of the personnel involved.

On Scene Observations:

Attachment 2 shows an overall view of the switchboard layout. There are twelve sections numbered left to right. Sections 3-5 contain the three main generator breakers. Sections 8 & 10 both contain eight molded case breakers and numerous ventilation switches and indicators. Sections 9 & 11 contain only ventilation louvers. In Section 12, there are twelve molded case breakers and numerous ventilation switches and indicators.

By the time the ship arrived at Ketchikan, all of the breakers and front panel covers had been removed and placed on the car deck. Some of the breaker supports in Sections 10 and 12 had been removed along with the breakers. There was severe smoke damage throughout the compartment. The ceiling and walls were soot black next to Section 12. The walls were less dark as you moved toward the opposite end of the compartment. Attachment 3 shows the damage to Sections 8-12 from left to right.

The overhead light fixtures in front of Sections 10-12 were melted as can be seen in Attachment 4. One can see that the entire ceiling is black. An overhead mounted monitor was partially melted and a PC was rendered inoperable due to soot.

The generators showed no external signs of damage. The number 1 & 2 generator breakers were disassembled and the contacts were examined. All of the contacts were in good shape with no evidence of abnormal operation, Attachment 5. The breaker arc arrester chutes were clean and showed no evidence of abnormal current flow entering or leaving the breaker.

The generator breakers were of Type FPS 50 and made by Federal Pacific. Breaker 1 was marked serial number WSC293001, Frame 1600, Max 600 V, Cycles 60, Current 1600. Breaker 2 was similar. Breaker 1 was recently overhauled and the old electro-mechanical trip circuit was replaced with a new model SSD Over current Trip Device. The SSD was marked as follows:

Time Current Curve # 1200B0750

Thumb wheel settings:

Function	Setting	Meaning	Actual Value
Instantaneous Pickup	4	10X	16,000 A
Short time pickup	1	3X	4,800 A
Short time delay	3	0.45 Sec	
Long Time pickup	5	1.1X	1,760 A
Long Time delay	4	10 Sec	
Ground Fault pickup	7	0.75	
Ground Fault delay	4	32 Sec.	

The M/V Columbia is diesel power ship with three main diesel electrical generators and one emergency generator. Each main generator is rated at 900kW, 0.8 power factor, 450 V, 3 phase, 60 HZ. The three main generators all feed into a single lineup of switchboards. Generators number one and two were on line at the time of the fire.

The formula for three-phase AC power is as follows:

$$Watts = Volts * Current * PF * \sqrt{3}$$

Next calculate the rated current of the generator.

$$\frac{900kW}{450V * 0.8PF * \sqrt{3}} = 1{,}443A$$

Using the rated voltage, current, and a power factor of one you are able to calculate that into a resistive load such as an arc, the generator is rated to produce 1.1 MW of power.

Testing by JHU/APL has proven that generators typically can supply 7-10 times their rated amperage for tens of seconds without damage. If we consider that two generators were on line and multiply times a minimum reserve amperage capacity of seven, it is calculated that approximately 20,000 amps could surge into the arcs within the switchboards.

The reverse current relays were tested for the COI three weeks prior to the accident. Mr. Roth-Roffy performed a visual inspection of the relays and found no problems. The trip indicators were found in the non-tripped position.

In switchboards of this type there are very heavy horizontal buses from the generators' breakers that traverse the bottoms of all of the sections. Vertical buses run up the side of Sections 8, 10, & 12. Horizontal bus bars run behind the supply side of the breakers and finger bus connects the breaker bases to the horizontal bus. There was no arcing damage to switchboard Sections 1-8. Attachment 3 shows Section 8 covered throughout with a thick layer of soot and metal oxides. Attachment 6 shows that the majority of the supply finger bus in the top of Section 10 was vaporized. A large hole was cut through the steel panel separating the bus from the ventilation controls in the top of the switchboard. Only small remnants remained of the ventilation controls that were mounted in the holes in the top of the panel. Attachment 7 shows a close up view of the hole above the top row of breakers. Attachment 8 shows that the supply bus connections to all four of the breakers in lower row were melted. While all of the load cables showed external thermal damage, the copper conductors within the cables showed no discoloration from an over current event.

Attachment 9 shows that there was no damage to the finger bus on the top row of breakers in Section 12 or to the partition between the bus and the ventilation controls compartment in the top of Section 12. All of the supply finger bus supplying the middle row of breakers was heavily damaged, as can be seen in Attachment 10. The finger bus bars connecting to the second breaker from the left on the bottom row were severed behind the breaker, Attachment 11. Attachment 12 shows the vertical bus on the left side of Section 12. Splatter damage can be seen on the side facing into Section 12, but none was seen on the opposite side. Behind that is the vertical bus in Section 10 where both splatter and arc damage can be seen. Each of the load cables were inspected and showed external heat damage to their insulation; however, none of the cables showed discoloration to the copper strands. Pieces of nylon cable ties were reported by NTSB to have been found in the bottom of the switchboard.

The photograph in Attachment 13 is taken looking down at the load side of the top row of breaker bases from Section 12. The left most breaker (P412) is the one that received the additional three conductors. You can clearly see two conductors attached to each phase of the breaker base. The cable lugs are correctly placed on opposite sides of the short piece of bus. All of the hardware and conductors are intact.

Attachment 14 shows pieces of breaker base tulip clips in various states of erosion by the arc current. Clip 1 is a complete clip that was removed from an undamaged breaker base. Normally the large diameter copper circular bar is imbedded in the molded breaker base. The end of the clip inside of the breaker base contains a spring-loaded set of petals that engage the breaker connections. The short piece of angle bus is bolted into the other end of the clip where the clip slightly extends through the base. Clips 2 & 7 show the angle bus and the bolt head partially eaten away by the arc. Clips 3 & 6 have been eaten down further and yet the bolt can still be seen within the clip. In Clips 4 & 5 you can see the internal threads. The head of a bolt completely separated by the arc can be seen beside Clip 6. Measurement of a good bolt show that it can only extend 0.8 inches into the clip when fully engaged. The threaded portion of the clip is 1.21 inches deep.

Attachment 15 is a photograph of a bolt found on the support angle just to the left of the second breaker from the left in the bottom row of Section 12, P442. The angle bracket can be seen in Attachment 11. The damage to this bolt is unusual in that the threads on the bottom side of the tip of the bolt are melted. The inside diameter of the two washers is melted (welded) to the bolt and there is melting damage to the bottom edge of the washer. The bolt contains a lock washer and a flat washer with an oversized outside diameter. This type of bolt and washer combination is used only within the switchboard to bolt the short piece of angled bus to the back of breaker and into the tulip clip.

Attachment 16 is a photograph of the far right hand side of Section 12. There was heat damage to the side of the switchboard and the finger bus bars were melted loose from the back of the breaker. On the left side of the photograph can be seen two cables that were previously tied up within the switchboard. These cables had been removed from the spare breaker in the top right corner of the switchboard so that their lugs could be used to complete the connection of the new cables to breaker P412. The mark on the side panel, beside the tip of the cable, is a scratch in the soot and shows no evidence of arcing. None of the strands of the three cables showed evidence of arcing.

Attachment 17 contains two views of the middle row of breakers in Section 12. One can see that there is damage to all of the tulip clips, but the most damage exists behind P456. One can also see that the discoloration area on the bottom of the breakers above extends farther up on the breaker above P456 than on the other breaker.

Ms. Nancy McAtee of NTSB reported that the deck underneath the switchboards was swept and vacuumed to collect small pieces of material. Two pieces of wire banding straps, approximately six inches long, were found in the bottom of Section 10. The bands are 0.48 inches wide and have small slots similar to a hose clamp. One piece of band showed evidence of arcing on the ends. NTSB reported that after rubbing the soot from the bands, they appeared to be bright bare stainless steel. A new sample cable strap was supplied by the shipyard for examination and was found to be Teflon coated. Testing showed the Teflon coating to be quite robust and to have an insulation value of greater than 2 million ohms. During a later examination of the strap pieces, it was found that the retaining clip was intact and still covered with Teflon. This confirms that the strap pieces found were of the same construction as the shipyard sample.

Origin of the Fire:

The origin of the fire was on the supply side finger bus behind breaker P456. This is determined by the fact that it is the only location that explains all observed damage, agrees with witness reports, and conforms to twenty years of test data.

When an arc is struck in the finger bus on the back of smaller breakers, such as contained in Section 12, the level of damage will peak at the point of origin. If a piece of metal is vaporized, it can create plasma that bridges the insulating air gap between two conductors. This allows electricity to flow through the plasma and creates an arc. While the arc exists, it continues to produce a cloud of conductive ionized gas, or plasma. This gas is composed of ionized air, vaporized metal, burnt insulator particles and gases, and free ions from the metal vapor and insulation vapor. The more sources of ions, the lower the resistance, and the higher the power in the arc.

As the plasma is generated, it expands somewhat hemispherically, depending upon confining materials. Since the plasma is a hot gas, it will expand more rapidly upward than downward. As the plasma cloud expands, it bridges additional conductors and additional parallel arcs can be created. Magnetic forces will drive an arc away from the source of current more rapidly than the expansion of the cloud. Therefore, if an arc struck first on the finger bus behind P456, location 2 on Attachment 18, the magnetic forces would drive it toward the back of the breaker. There, the combustible material would lower the plasma resistance and increase the power of the arc. The cloud would now expand horizontally behind the breaker; however, the magnetic forces would drive the arc to the right and cause the plasma to expand more rapidly in the right direction, locations 5 to 6. Eventually, the arc would reach the far right and side of the switchboard and begin to damage the side panel beside of the finger bus. The centroid of heaviest damage would be behind P456. A skewed Gaussian distribution curve could be drawn across the damage with the peak at the P456 location. If the arc has struck anywhere else in Section 12 and moved to the location behind P456 there would have been small barb marks of 0.010-0.050" in size on the bus marking the direction of passage. No such marks were apparent.

Some of the molten metal from the arc is not vaporized, but just drops. Part of the molten metal from P456 dropped and created an arc on the source side of P442, location 4. While the bus behind P442 was damaged, the plasma cloud had not developed enough to bridge to any of the adjacent possible locations. Therefore, the arc at P442 happened late in the chain of events. See Attachments 9-11.

There were arc splatter marks on the right hand side of the vertical bus on the left side of Section 12, Attachment 12. These marks were in a line of sight of the arc on the back of P456. Additional splatter marks were found on the right hand side of the adjacent vertical bus in Section 10, location 8. Arc travel marks were found on the vertical bus in Section 10 showing that the arc moved up and out onto the finger bus. No arc travel marks were found on the vertical bus in Section 12. No arc splatter marks were found on the left-hand side of the vertical bus in Section 12 and the arc did not travel up the vertical bus in Section 12. Therefore, the arc could not have initiated in Section 10 and traveled to Section 12.

In Section 10, vertical supply bus bars come up both sides of the switchboard. The resultant magnetic forces retard the travel of the arc on the finger bus. As the arc slows down, the heat becomes more localized and the damage rate goes up. The plasma enveloped the source finger bus of both rows of breakers at locations 9 and 10. When the plasma along the upper finger bus touched the top panel at location 11, the panel became an intermediate conductor for the electricity. A typical current path would be from phase A to the switchboard and back to phase B creating two arcs. Each of these arcs would continue to consume bus and switchboard frame, resulting in a large hole in the top panel. This has been confirmed in many

JHU/APL tests. The arcs is Section 10 would tend to suck some of the power from those in Section 12 and the Section 10 arcs have a lower impedance path back to the generators. This helped to prevent the arcs in Section 12 from growing large enough to jump the gap onto the top set of finger bus at location 7. There was no hole in the top panel at location 7.

This explanation links all of the observed data in a sequential order, which agrees with basic physics and the testing at JHU/APL. It also agrees with the two eyewitnesses who reported that the first flash occurred from Section 12 and was followed a few seconds later by a flash from Section 10.

Causes Ruled Out:

Based upon the observed facts above, the results of over 2000 arcing tests conducted, and numerous prior electrical fire investigations, we will examine the likelihood of the possible causes.

1. The casualty was not in any way related to a short on a load, load cable, or equipment failure outside of the switchboard. If a cable experienced an overload condition, the strands of the conductor would heat up and change color due to the thermal stress. Each of the load cables in Sections 10 & 12 were examined and none contained discolored strands. In addition, the breakers would have tripped before the cables to the switchboard could be damaged due to a defective load. Therefore, an over current event outside of the switchboard did not cause the arc inside of the switchboard.
2. The Chief Engineer reported that sometime during or immediately after the fire he felt the load cables leaving the switchboard on the side of the bulkhead opposite from the switchboard and found that the new T200 cable was "a lot warmer than the others." The new T200 cable was in parallel to an older T200 cable. If there had been a fault at the load end of the cables, the current should have been shared equally since both ends of the cables indicated that the connections were good. If the current had been high enough to cause a fault in the switchboard, it should have tripped the breaker and prevented the fault or left discoloration of the cable strands inside of the switchboard. Neither happened so the new T200 cable was not at fault.

   Another reason against the significance of the perceived cable temperature difference is the cable construction. The new cable was unarmored while all of the older cables were armored. One could observe that the armor inside of the switchboard was burnt. It produced a fuzzy look to the surface of the cables. Ablating the armor inside of the switchboard absorbed heat that otherwise would have gone into heating the cable. This would reduce heat reaching the outer compartment where the cable was felt. Additionally, a metal surface has a higher thermal conductivity than plastic. This will make the metal surface cooler to the touch than a plastic surface and could account for the perceived difference in temperature.
3. It was postulated that some type of reverse current between the two generators might have caused the fault to occur. The reverse current protective relays were tested three weeks prior to the fault and were found to be satisfactory. Upon visual inspection they still appeared to be in working order. If a reverse current event had occurred then

the mechanical trip indicator flags should have been set. Since the trip flags were not set, the fault most likely was not related to a reverse current event.

4. The two generators were reported by the ship's personnel to have been jumping during the fire. This led to the supposition that the two generators fighting against each other may have caused a voltage spike that initiated the fault. The voltage regulation circuit should have maintained the voltage close to the specified 450 V value. At the closest, the bus bar separation was approximately ½ inches. The insulation value of air under the worst case exceeds 20,000 volts per inch. Therefore, the generators would need to produce greater than 10,000 volts to jump the gap and initiate the fault. Short voltage spikes appear from time to time on the line, and are associated with switching loads on and off. No load switching was occurring to the plant lineup immediately before the fault; and it is very doubtful that the generators produced the necessary 10,000 volts needed to initiate the fault.

5. At first examination, some people felt that the mark on the side panel of Section 12 adjacent to the bare end of the cable was an arcing mark, Attachment 16. The cable in question was an unused load cable and not a source of power. A closer examination of the mark revealed that it was a scratch caused by the falling of the spare cable. During the rework of P412 this cable was removed from the spare breaker base and secured up in the switchboard with nylon cable ties. Cable tie marks were found on the cable and pieces of nylon ties were found in the bottom of the switchboard. The most likely scenario is that during the fire, the low temperature nylon tie melted and allowed the cable to fall down and scratch the soot previously deposited on the side of the switchboard. This had to occur late in the event or the mark would have been covered with soot. Since the cable had no power and it fell down late in the event, it was not the initiator of the fault.

6. When JHU/APL examined the switchboards, the deck had been swept clean and all small debris removed or deposited into a couple of five-gallon buckets. JHU/APL relied on the NTSB report for identification and origin of individual parts of the debris. The field report by Ms. N. McAtee states that wiring banding material was found on the deck underneath switchboard Section 10. Note that the eyewitness reports state that the fire was first seen in Section 12 and later in Section 10. It was postulated that the two pieces of metal cable tie found with arcing damage could have started the arc as a result of their falling down and shorting the bus.

There were three types of cable ties used in the switchboard. The first was a common nylon tie. Numerous pieces of nylon ties were found in the buckets and the marks where they had been in place could be seen on the damaged cables. The second type was a smooth bare stainless steel strap that must be tightened with a strapping tool. A piece of rubber cushioned the cables from the strap. No damage was found to this type of strap. The third type of tie was a long stainless steel strap with slots in it much like the slots on a common hose clamp. One end of the strap has a clip through which the opposite end of the strap is threaded after the cables are encompassed. The clip contains a locking paw that allows the strap to be pulled tight and retains the strap tension. One might view this strap as a larger metal version of the nylon cable tie.

ASD supplied a sample of the standard shipyard strap and it was found to have a tough Teflon coating. Tests showed that the coating had an insulation value greater than two million ohms. The arced pieces of cable strap were first reported to be of bare bright steel. Later closer examination of the straps by JHU/APL revealed that one of the pieces still had the closure clip. The clip was the same type as the shipyard sample and was coated with Teflon. Therefore, it is concluded that the burnt strap was originally coated with Teflon that was melted during the fire. JHU/APL attempted to strike an arc by placing a sample of the Teflon coated strap across bare bus bar without success. The location where the cable tie pieces were found is not compatible with the origin of the fire. The Teflon insulation on the metal tie should protect the tie from shorting the bus. JHU/APL testing showed the effectiveness of the Teflon insulation in insulating the tie from the bus. Therefore, the metal tie piece must be ruled out as the primary cause of the fire.

7. It was postulated that the fire was related to the rework of breaker P412. During the rework, it was necessary to remove the original cable lugs from the load side of the breaker and to attach one additional lug to each phase of the breaker. Attachment 13 shows that all six cables and lugs on the load side of P412 were found to be intact and without damage. All breaker base hardware was present and accounted for and thus could not have been the cause of the fault. However, it is not possible to determine if as a result of the rework some hardware was left loose inside of the switchboard that later fell down and caused the fire.

8. If a molded case breaker such as used in these switchboard suffers an internal failure, it can expel enough plasma to create a phase to phase arc and create this level of damage. Note that in Attachment 17 breaker P456 shows no damage to the top surface near where the arc began. Each of the damaged breakers was disassemble and inspected for internal damage. None of the breakers showed evidence of internal faults, therefore the fire was not caused by a breaker failure.

Most Likely Causes of the Fire:

With the origin of the fire established as the source side finger bus behind breaker P456, let's look at the most likely causes.

Analysis of over twenty-five years of major electrical fires on U.S. Navy submarines resulted in the finding that 60-80% of all electrical fires were caused by a faulty connection. Faulty connections are those where the resistance of the connection has increased and caused localized overheating. This increase in resistance can be caused by poor initial torque in the connection, corrosion, and loosening of the connection. The ship's load switching, vibration, oxidation, and salt atmosphere corrosion work together to make the connection progressively worse over time. At some point the resistance of a joint becomes high enough to cause localized melting of the bus which leads to localized arcing. This is a relatively small series, or inline, arc that is limited in size by the amount of current that can go through the load. The arc generates plasma until the plasma cloud expands to bridge the gap between adjacent bus bars, which causes a phase-to-phase arc. Once the arc strikes phase to phase its supply of current is limited only by the size of the generators. It is at this time that the major damage is done. This type of fault requires that the load be active, as was the case with P456. This type of fault is most likely to occur in smaller breakers, such as P456, when initially closing the breaker as the load presents a large inrush of current that pushes the compromised joint beyond its capabilities. Breaker P456 had been steadily online at the time of the fault, which makes a loose connection much less likely to be the cause of the fault. While a loose connection can not be totally ruled out as the cause, the existence of an unusually damaged bolt, discussed next, makes another cause much more probable. If one accepts a loose connection as the initial fault, one is left with great difficulty in explaining the existence of the bolt. If one postulates that both a loose connection and the loose bolt caused arcs, then one must accept that two unusual events occurred at the same time, which is improbable.

A loose bolt, Attachment 15, was found on an angle brace just to the left of the top of breaker P442, Attachment 11. This was the only loose bolt found in one piece and it had unique arcing damage. All other bolts found with arcing damage were either in pieces or still installed in their original positions. Attachment 19 shows a scale drawing of the finger bus with the bolt and washers lying across the bus. Note that if the bolt were to lie on its side the washers would cock over at an angle as shown. As current flowed from one bus to the other through the bolt, it would leave arc damage at the points shown. When the washer is cocked on the bolt the current is forced to flow through the sharp corner of the washer inside diameter, ID. This concentration of current will produce localized overheating that welds the washer ID to the bolt. With the light weight of the bolt, the gas pressure from the arc generally kicks the bolt up and off of the bus. The bolt tends to rotate around its heaviest point, the head. Note that the observable damage to the bolt in Attachment 15 agrees with the postulations in Attachment 19. The most likely cause of the fault is that the bolt in question fell down across the finger bus behind P456 and initiated an arc. The bolt was tossed off of the bus and landed down on the angle iron where it was later found and the arc proceeded as explained under the arc origin section of this report. This scenario was duplicated in JHU/APL testing.

Even if the bolt's importance as the arc initiator is ignored; the origin of a loose bolt in a switchboard must be determined. This bolt and washer stackup is unique to the bolts used in the connections on the back of the breaker bases and could not have come from the switchboard frame. One could postulate that the bolt came loose from one of the breakers in the row above P456; however, all of those bolts were found in their proper positions. Another possibility is that the bolt came from the back of P456. Refer back to the array of tulip clips shown in Attachments 14. It is theoretically possible for the vibration of the ship to back the bolt out of the tulip clip. However, once the torque in the connection has been reduced to zero the connection will drastically overheat and fail. That type of failure should produce the type of damage shown in Clip 6. There would have been enough heat that the loose bolt could not fall out of the clip before a series arc in the connection melted the bolt and bus.

If the bolt didn't vibrate loose from its original position then it must have existed loose in the switchboard. There are several places above the location the arc began that a bolt could rest. Two angle irons span the width of the switchboard above breaker P456 and the bolt could have rested on the angles. There are three rows of tulip clip insulators with horizontal surfaces above the finger bus of P456, the two rows of the top row of breakers and the top surfaces of breaker base P456. A bolt could have rested on the top surface of these clips or have been wedged between two of the insulators. From any of these positions the ship's vibration could have caused the bolt to "walk" off the edge of its ledge and fall onto the finger bus where it started the arc.

When the bolt was left inside of the switchboard is impossible to determine. It is possible that when ADS performed work on P412 and the spare that they removed tulip clip mounting bolts for easier access to their work. A bolt could have become lost in the switchboard and ADS could have replaced the bolt from their stock without finding the lost bolt. It is not known how difficult it would be for ADS to secure a replacement bolt. If the bolt were lost earlier in the switchboard, it could have become wedged between two of the insulators. It could have existed in the switchboard for years before the ship's vibration caused the bolt to come loose and drop.

The question was brought up that the ship was in calm water at the time of the fault. One opinion was that any loose bolt should have fallen under rough sea conditions. It is agreed that ship's roll will cause loose material to shift its position. However, the ship's vibration is more likely to cause wedged material to creep from position. For example, one might expect that the ship experienced some motion during its tow to Juneau and then to Ketchikan, but the bolt remained perched for a week on the angle where it was later found. Therefore, it is submitted that the bolt could have been wedged in the switchboard for years or could have simply lain loose for the few weeks the ship had been in service.

Generally when an arc is started by a loose connection the faulty connection is vaporized. Therefore, one concludes that a loose connection was at fault only after ruling out all other possible causes. Here we are sure that the arc damaged bolt caused a fault across two bus bars. It is highly unlikely that the bolt came from a functional position. It is most likely that it was a loose bolt. Therefore, it is most likely that the bolt was the primary cause of the fire.

Generator Breaker Operation:

Large breakers, such as used to protect the generator, generally contain at least three types of trip elements. The current for this breaker had to exceed 16,000 A to trip in less than 50 milliseconds. If the current exceeded 4,800 A for 0.45 seconds the breaker should trip. The long-term pickup is the value below which the breaker will operate forever. These breakers had to exceed 1760 A for 10 seconds to for them to trip. If the breaker exceeded reached 4,000 A for 9 seconds and then returned below 1,760 A, then it would not trip. The current could oscillate between 4,000 A and 1,500 A and as long as the duty cycle was no more than 9 seconds at the higher value the breaker would not trip. Oscillations of just under 16,000 A could be permitted by the breaker as long as the maximum duration of the spike did not exceed 0.45 seconds. The wild rocking of the generators is confirmation that wild fluctuations in current existed. This has been duplicated in JHU/APL test using GE brand generators.

The breakers were originally manufactured by Federal Pacific, not related to the Federal Pacific located in Bristol, VA. Reliance Electric owned Federal Pacific for four years a long time ago and no one there knows anything about the breaker in question. Challenger Electrical

Equipment next owned the breaker line. The molded case breaker products were retained by the part of Challenger who was absorbed by Cutler-Hammer, Eaton. They have no knowledge of the air circuit breakers like used on the M/V Columbia. Many other companies have repaired and serviced the product over the years. The only company located that is presently associated with this breaker is Elenco (telephone 516-519-8102). They repair Federal Pacific breakers, but have no design information.

The back of the breakers stated that time current curve #1200B0750 was the applicable curve. The tech manual contained curve #1200-B-0785. While this is not the exact set of curves it is felt that it is close enough for this analysis. Based upon the available data, Attachment 20 contains our best estimate as to the trip curve of the breaker. Only time current values to the right of the curve will cause the breaker to trip. That leaves a wide range of values to the left where large arcs can exist without tripping the breaker and as well as short transients to the right.

As the plasma spread through out the switchboard arcs were constantly striking in new locations on the bus bars. Sometimes multiple arcs existed at the same time. This was demonstrated at the tests NTSB witnessed at JHU/APL. The striking, cessation, and restriking of arcs causes wide variations in the total current flow into the switchboard. The combination of the reserved capacity of the generator and the inverse time delay trip curve of the breakers can permit the arcing event to exist for an extended time. Breakers can not distinguish the inrush surge in current from a motor from the surge in an arc. In these power levels there is no breaker that can uniquely distinguish an arc from normal events and stop the flow of current.

Testing at JHU/APL:

To confirm the damage pattern to the bus and the bolt, two tests were conducted at JHU/APL. In each test, two pieces of bus were bent upward at ninety degrees similar to the back of the tulip clips. A bolt and washer, similar to the loose one found in the switchboard, were placed across the bus. A DC voltage of approximately 225 V at approximately 1,700 amps was supplied to the bus. This represent 1/30-1/40 of the peak power available on the M/V Columbia. In each case the bolt was kicked up and toward the heavy end of the bolt. The arc moved quickly to the short vertical portion of the bus where its motion stopped, Attachment 21. Considerable damage was done to the bus during the one-second test. In each case the washers were lightly welded at an angle in the position postulated in Attachment 19. If the power had been higher the weld would have been stronger. Note that in each case debris and gas from the bolt created arc caused a second arc to strike on the vertical bus a foot away from the first arc. At no time did the arc back track on the finger bus.

A similar test was conducted with a piece of unused Teflon insulated cable tie across the bus. As expected no arc occurred. The test was repeated two more times using a piece of bare stainless steel hose clamp similar to the cable tie. In each of these two tests the arc struck and did similar damage to the bus as in the bolt tests. In each case the strap was damaged, but thrown clear of the arc initiation point, Attachment 22. A total of fourteen people from NTSB, USCG, ATF, AMH, and ASD spent a day at JHU/APL to witness these tests and to discuss the results.

It was suggested that the test be conducted by actually dropping the bolt onto the bus. First, this would require the design and fabrication of a device to accurately drop the bolt onto the bus. The power levels are too high to perform this test manually. Second, we can't allow the test time to run open ended without incurring considerable expense to repair the damage and greatly increasing our safety hazard. Therefore the duration of each test is tightly controlled to be no longer than one second. Design of the bolt drop mechanism would have to include the capability to link into our arc control system. This test could be conducted, but is beyond the scope of this contract. Electrically the test should be the same whether the bolt is dropped or placed on the bus.

Missing Data:

The maintenance logs for the switchboard were reported to be on the ship's computers and copies were not available at the time of the investigation. It is reported that only high level information on switchboard maintenance was kept in the log; therefore, it is not likely to shed any useful new information. It would be very useful to know if any breaker base was ever replaced, but we were told that that information is unlikely to be in the log.

We were told that a printout existed from central alarm system. Since the loss of power to some systems would show up in the printout, examination of this printout might help to confirm the sequence of events after the initial electrical failure. The personnel on site at the time of the fire reported no alarms before the fire, so the alarm printout would not help determine the cause of the fire. It could only possibly confirm the propagation and duration of the fire.

We were unable to obtain access to an actual time-current curve for the generator breakers. The estimates of available current are based upon typical curves and the breaker labels. It is believed that actual curves would only change the values by 10-15% and have no real affect on the overall analysis.

A vessel condition survey was performed several years ago. Mr. D. Reichl of AMHS reported that it shed no useful information on the condition of the switchboards. The only piece of missing information that might be useful would be to interview all personnel associated with the recent rework of P412. Someone might shed some information as to the possible source of the loose bolt. Due to the inherent fault finding associated with this information, it is doubtful if the source of the bolt will be found.

Concerns:

As a result of this investigation several concerns come to light. It was reported that the most recent switchboard inspection occurred in 1995. The switchboard manual states that "Switchboards should be cleaned and inspected annually." Annual cleaning and inspections are required of all Navy switchboards. NTSB should look for a way to make the annual maintenance occur. Ways to increase training in the awareness of the safety hazards of the switchboard should be considered.

As a result of inspecting ship's loads for possible contribution to the fault, panel P2 was found to be in need of rework. Two breakers had loose wire strands sticking out of the connections on the side of the breakers. One breaker had a corroded connection. Another breaker had insulation inside of the connection that reduced the amount of copper wire in contact with the breaker terminal.

The ABT was reported to shift several times during the event. Flickering of the lighting confirmed the ABT transitions. The ABT was set for a 1% difference, which helped cause, the circuit to shift back and forth as the main voltage fluctuated with varying arc load. Rapid chattering of the ABT may have damaged the contacts and they should be inspected.

Conclusions:

The generator breakers operated per their specification. Any adjustments to their settings would result in nuisance trips. Any new design for these switchboards would result in similar breakers and settings. Generator breakers will not protect switchboard against electrical fires. Testing by JHU/APL and twenty five years of recorded Navy history confirm that the arc is not a bolted fault and will not trip the instantaneous trip coils of the larger breakers. Breakers are effective against low impedance bolted faults, but offer no protection against high impedance arcing faults.

There is no evidence that any errors by the ship's crew caused the fire to occur. The damage to the bus and switchboard enclosures occurred within less than a minute. Carbon Dioxide fire extinguishers will not stop an electrical fire. One must first remove the source of electricity as the ship did by cutting one generator. Since they have a single plant lineup, they should have cut the second generator at the same time. This may have reduced the level of damage, but it would not have changed the level of component replacement needed. Once power is removed one can fight the burning cables, breakers, and insulation with the extinguishers.

The basic cause of the fault was the existence of a loose bolt. Once that shorted the bus the damage proceeded in a fashion predictable from numerous JHU/APL tests and previous Navy switchboard fires. A loose bolt should never have existed inside of the switchboard. This bolt should have been found during the close out inspection of the switchboard after the work was completed in April 2000. Safety awareness by the shipyard and the ship needs to be reinforced. They should always treat work in the switchboards carefully. Before the switchboards are closed all parts and tools should be accounted for. The Navy goes so far as to require that a second person perform a close out inspection after the inspection by the workers.

Navy has initiated the use of Glyptal on all bare bus. This reduces the likelihood of the initiation of an arc due to a fallen object, but it will increase the damage if an arc should occur.

It helps to lock threaded fasteners. NSTB might consider requiring Glyptal coating of bus bars and connections.

As shown by this fire and numerous fires on Navy ships, manual intervention will not prevent or even minimize the damage should an electrical fire occur. Careful close out inspections, annual cleanings and inspections, and thermal imaging can reduce the frequency of occurrence of this type of electrical fire. However, the Navy has learned over twenty five years of investigation that these alone will not prevent the occurrence of arcs. Only an active arc fault detection and prevention system can minimize the damage and it can frequently prevent the damage from occurring. Until recently AFD/CTM systems have been designed narrowly for the Navy applications. Now components and systems exist that are suitable for commercial marine and land based application.

Navy Electrical Fire Background Information:

JHU/APL began working for the Navy in 1979 to determine if it were possible to detect an electrical fire in time to limit the damage to a manageable level. Navy data show that significant arcing casualties have been reported in submarine on an average of 2.6 times per year since 1975. JHU/APL investigated many ways of detecting arcs to determine which ones would best detect arcs, while ignoring the normal shipboard background environment. Light was investigated at wavelengths from IR to UV. Pressure, temperature, noise, radiated emissions, conducted emissions, voltage waveform changes, current waveform changes, and magnetic fields were investigated as indicators of arcing activity. An Arc Fault Detector, AFD, System was designed based upon the combined signals from narrow band UV emissions and pressure. Fleet installations began in 1990. Navy procured these systems by competitive biding and all SSN 688, SSBN 726, SSN 21, Virginia Class and the SSN 683 have been outfitted with AFD Systems. Over 80 submarines have been outfitted with 4-12 AFD Systems on each ship. The Navy presently has over 500 ship years of AFD System operation without a false alarm. The systems have prevented major damage on ships nine times since 1993. The reliability of this system is so high and the function it performs is so vital, the Navy allows this system to pull the power from any switchboard on the submarine that experiences an arc.

The Navy recognized they had a worse problem with electrical fires in the nuclear aircraft carriers, where fresh air is used to cool the machinery spaces containing the switchboards, than on the submarines. The Navy created a committee of over twenty players to investigate causes and fixes for the problem. Many years of investigations produced several changes to the switchboards, but no cessation of the fires. In 1999, the Navy had a major electrical fire in what was considered to be the perfect switchboard. All of the design improvements that had been postulated to be effective had been incorporated into this switchboard. This leads to the conclusion that it may not be possible to design a switchboard that is impervious to an arcing fault.

In 1996 JHU/APL was asked to design a new lower cost AFD System which would make extensive use of Commercial-Off-the-Shelf, COTS, components and subassemblies. At about the same time JHU/APL was tasked to determine if there was a way to detect arcs before they happen. Analysis of the Navy casualty data determined that 60-80% of all arcs begin due to a faulty connection. The faulty connection creates heat. JHU/APL has designed a Thermal Ionization Detector, TID, which can detect the outgassing of overheated insulation before it fails into an arc. The TID allows Continuous Thermal Monitoring, CTM, of switchboards for faulty connections. This became the AFD/CTM System that was deployed onto the new Virginia Class Submarines and for the carrier system. The design for the carrier AFD/CTM System has been completed and approved. As the result of the fire in the perfect switchboard, the Navy is beginning production and deployment of the carrier AFD/CTM System.

ABB, a foreign switchboard company, is the only other known source of equipment to protect switchboard against arcing failures. Their present system uses an optical fiber to detect light from an arc and pull the upstream breakers. While the ABB Arc Guard System has been available in Sweden for about 15 years, like most safety systems, it has not been widely accepted. France, Indonesia, and Sweden are the largest users. The system has just recently been marketed in the U.S. and only two systems are reported to be in service. The latest class of super cruise liners uses all ABB switchboards and makes extensive use of the ABB Arc Guard System. To the cruise liner industry down time is measured in millions of dollars of lost opportunity. While safety is important, they are also concerned with avoiding the cost and down time of repairs and they have recognized that some form of arc fault protection enhances ship availability.

There are some major differences between the approaches of ABB and JHU/APL. The ABB systems see the light and pull the breaker. There is no false trip protection against slightly off-normal flashes from air circuit breakers. The JHU/APL systems are proven to ignore slightly off-normal breaker flashes, but pick up bad breakers. The JHU/APL systems all incorporate a Built-in-Test, BIT, which assures the system is on line and fully functional. The ABB system does not have built-in-test functions. The JHU/APL system can be wired to a centrally located control unit for easy monitoring. ABB uses a multitude of smaller local control chassis. The JHU/APL system is designed for a systems approach to the electrical plant, which allows a zoned approach to load shedding. The ABB system protection is geared more at the local level. Only the JHU/APL system incorporates a method of continuous monitoring the switchboards for hot spots and thus preventing arcs. Only the JHU/APL system has received approval for connection to nuclear related switchboards. Both systems can be used in existing switchboards or installed in new switchboards in the factory.

Since there are differences in capabilities, it is difficult to compare prices between the two systems. The ABB system is in current production for use in commercial installations. The newer carrier AFD/CTM System is not yet in production, so it's price can only be estimated. It is our best estimate that, in its present form, the cost of the JHU/APL system will be a bit higher in small installations and lower in larger installations. While the JHU/APL AFD/CTM system was designed for the Navy, it could be used without modifications in commercial marine and land based installations. However, the system could be modified for the less severe commercial environment with resultant cost savings.

The switchboard manufactures for land based systems recognize arc faults as a major problem. Their solution is to sell specially reinforced switchboards that have pressure relief panels to help them survive the explosion. They also make use of switchboard compartmentalization similar to Navy switchboards. This helps to isolate the damage to a smaller area. These products are marketed as "arc resistant" switchboards. These techniques can not be backfit and are of no use in protecting existing switchboards.

Navy requires that all switchboards be cleaned and inspected once a year. They perform thermal imaging of all switchboards every two years. Thermal imaging always finds problem areas that must be fixed.

There are problems with thermal imaging. The cost and availability of trained manpower has limited the Navy to performing imaging only every two years. Imaging must be done when all loads are active, the switchboard covers are off, and the switchboards are at operating temperature. This is hard to accomplish dockside. The need for the operator to use imaging equipment within 12-18" of bare energized equipment at sea presents safety issues. Only about 50% of the connections are in the direct line of sight needed for imaging. There have been several cases where electrical fires occurred only a few days after the switchboard passed thermal imaging. This indicated that thermal imaging can identify some, but not all, precursors to an arcing event due to the limitations inherent to the technology. In spite of all of this, thermal imaging is still very worth while.

Over the past twenty-one years that JHU/APL has supported the Navy in the investigation of arcs, over 1300 memos detailing testing, testing results, and AFD/CTM systems designs have been generated. JHU/APL has conducted over 2000 arc tests at currents from a few hundred amps to over 30,000 amps. Tests have been conducted with both AC and DC voltages from 100 V to 4160V. Navy has witnessed many of the tests. Many arc tests were photographed at 4000 frames per second and then studied one frame at a time. These tests give us a unique perspective on the creation and propagation of arcs in switchboards. Over 1500 engineering drawings have been generated documenting the many implementations of AFD/CTM technology. All of the JHU/APL designs have been reviewed and approved by the Navy electrical and nuclear department. We have investigated and documented over two dozen major electrical fires. While none of this data is classified, some of it is sensitive and can not be released to non-government personnel without Navy approval.

Sincerely,

H. Bruce Land III

H. Bruce Land, III
JHU/APL
Arc Fault Detector
Program Manager

Attachment 1

http://www.dot.state.ak.us/external/amhs/home.html
http://www.dot.state.ak.us/external/amhs/updates/specials/index.html#changes

June 13, 2000

A minor fire aboard the M/V Columbia has been extinguished, and all 434 passengers and 63 crew members aboard are safe. Passengers were transferred to the M/V Taku and will be returned to Auke Bay ferry terminal in Juneau by approximately 8:00 p.m. tonight. The M/V Columbia is stable, but does not have propulsion power.

The US Coast Guard and the M/V Taku are at the scene. Two tugboats have been dispatched and the Columbia will be towed to Auke Bay where vehicles will be unloaded and damage assessed. Information about passengers aboard the Columbia and be obtained by calling either (907) 465-8822 or (907) 789-5002.

Please check our press releases or the Main Schedule Menu for complete information on schedule changes. To make a reservation please contact the Alaska Marine Highway by calling toll-free: 800-642-0066, make a reservation request online, or contact your local terminal.

http://www.dot.state.ak.us/external/amhs/news/releases/pressrelease6600.html

Press Release - June 6, 2000
Alaska Marine Highway
System (AMHS)

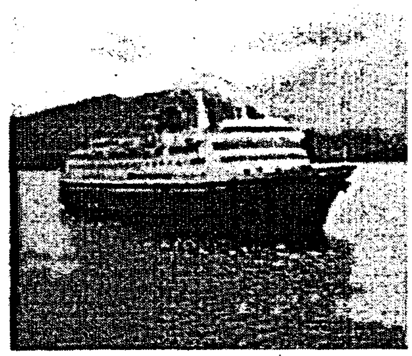
M/V COLUMBIA
SUSTAINS MINOR FIRE

The Alaska Marine Highway System reports all passengers have been safely evacuated after a minor fire aboard the M/V Columbia. The fire has been extinguished and all 434 passengers and 63 crew are safe. The fire, which originated in the main switchboard of the control room, was reported at 12:40 p.m. today. The M/V Columbia is stable but does not have propulsion power.

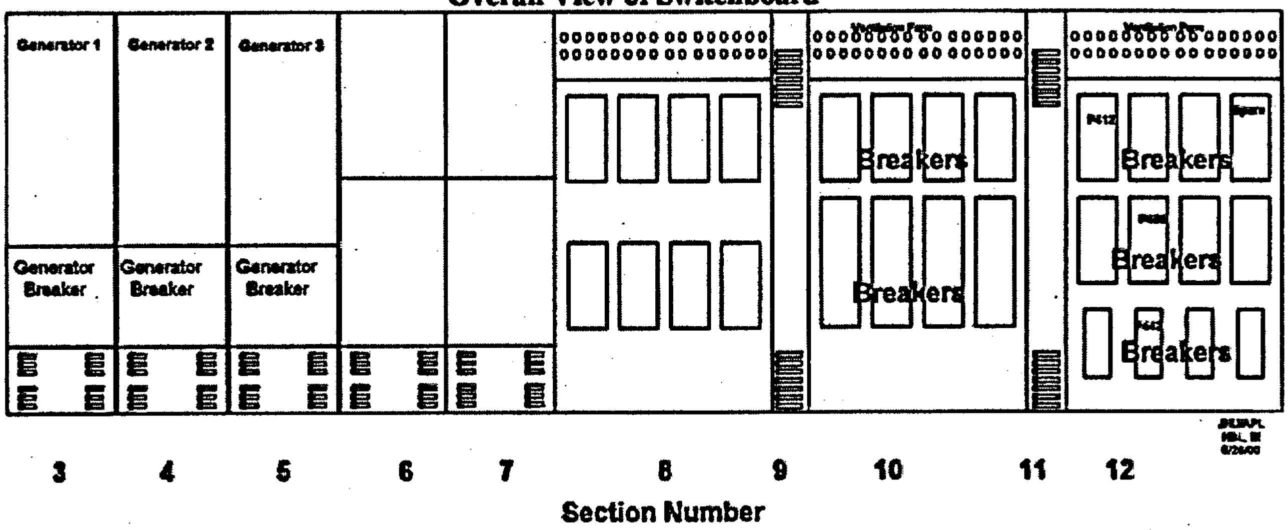
The U.S. Coast Guard and M/V Taku are at the scene. The Columbia was en route from Juneau to Sitka when the incident occurred. The Columbia is currently located approximately 3 miles north of Tenakee Inlet in Chatham Strait. Passengers were transferred to the M/V Taku and will be returned to Auke Bay ferry terminal in Juneau by approximately 8:00 p.m. tonight. Two tugboats have been dispatched and the Columbia will be towed to Auke Bay where vehicles will be unloaded and damage assessed.

Further information on the vessel will be released as soon as possible. Information about passengers aboard the Columbia can be obtained by calling either (907) 465-8822 or (907) 789-5002.

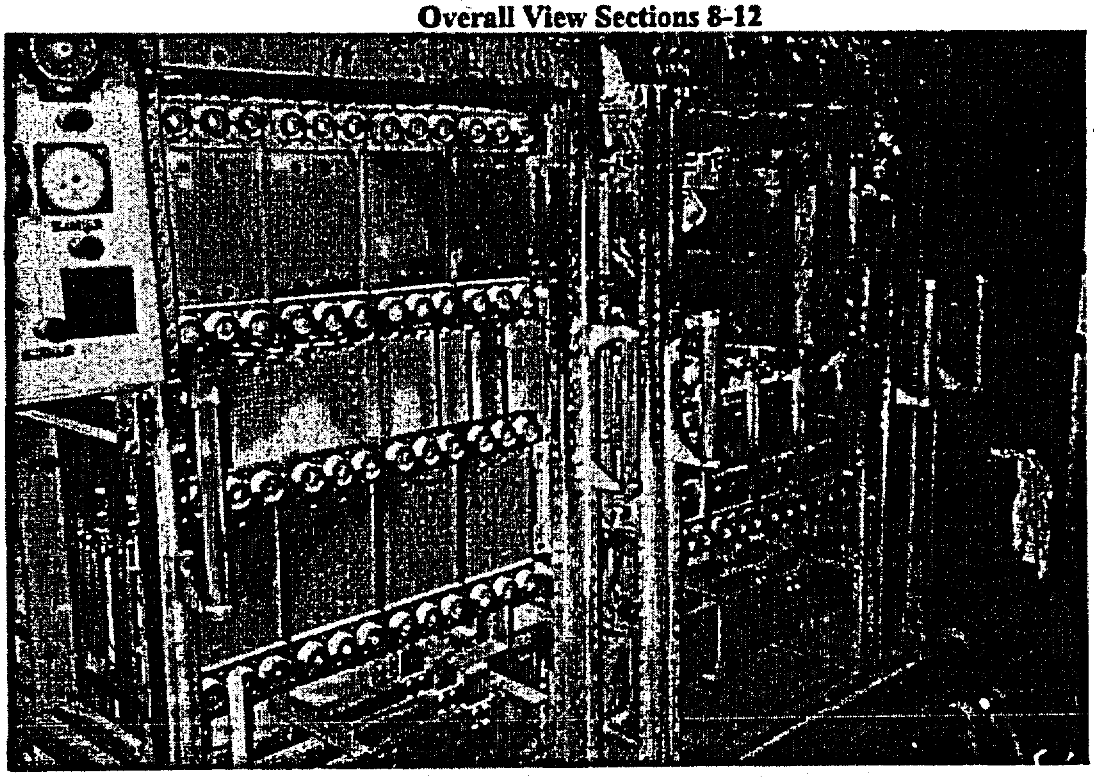
The M/V COLUMBIA is the largest vessel of the Marine Highway fleet. Launched by Lockheed Shipbuilding in Seattle in 1974, the Columbia is 418 feet long, with capacity for 625 passengers and 134 vehicles (20' lengths). It is also the fastest vessel, operating at a service speed of 17.3 knots. Its 91 total cabins include 60 four-berth units, nine 3-berth units, and 22 two-berth units. The Columbia boasts both a fine dining room and a cafeteria. The gift shop, cocktail lounge, solarium, and forward observation lounge round out the passenger amenities.



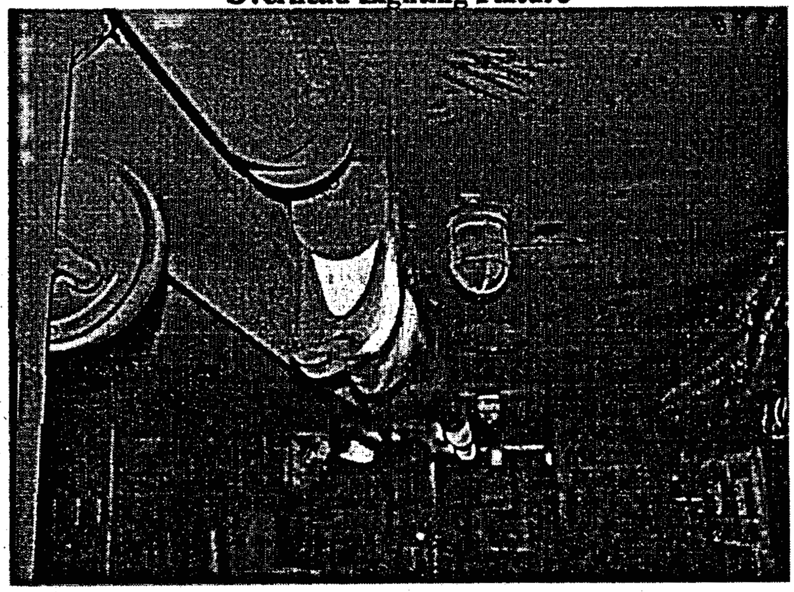
Attachment 2
Overall View of Switchboard



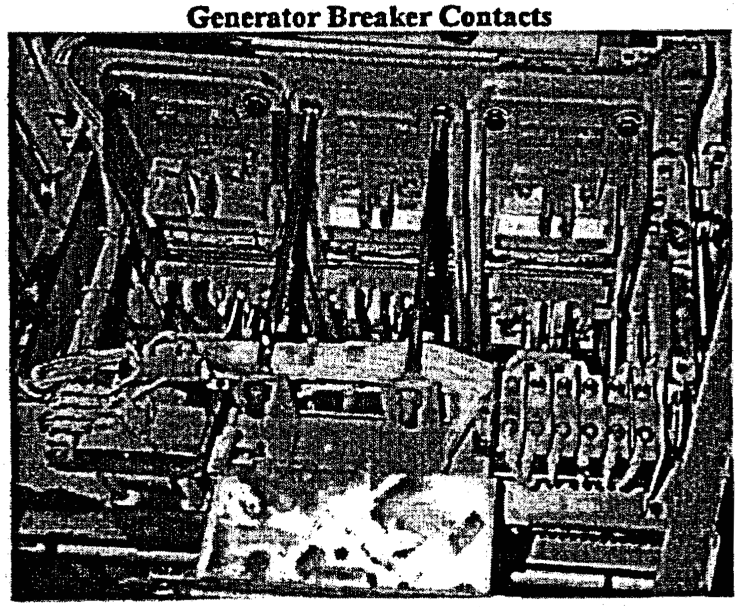
Attachment 3
Overall View Sections 8-12



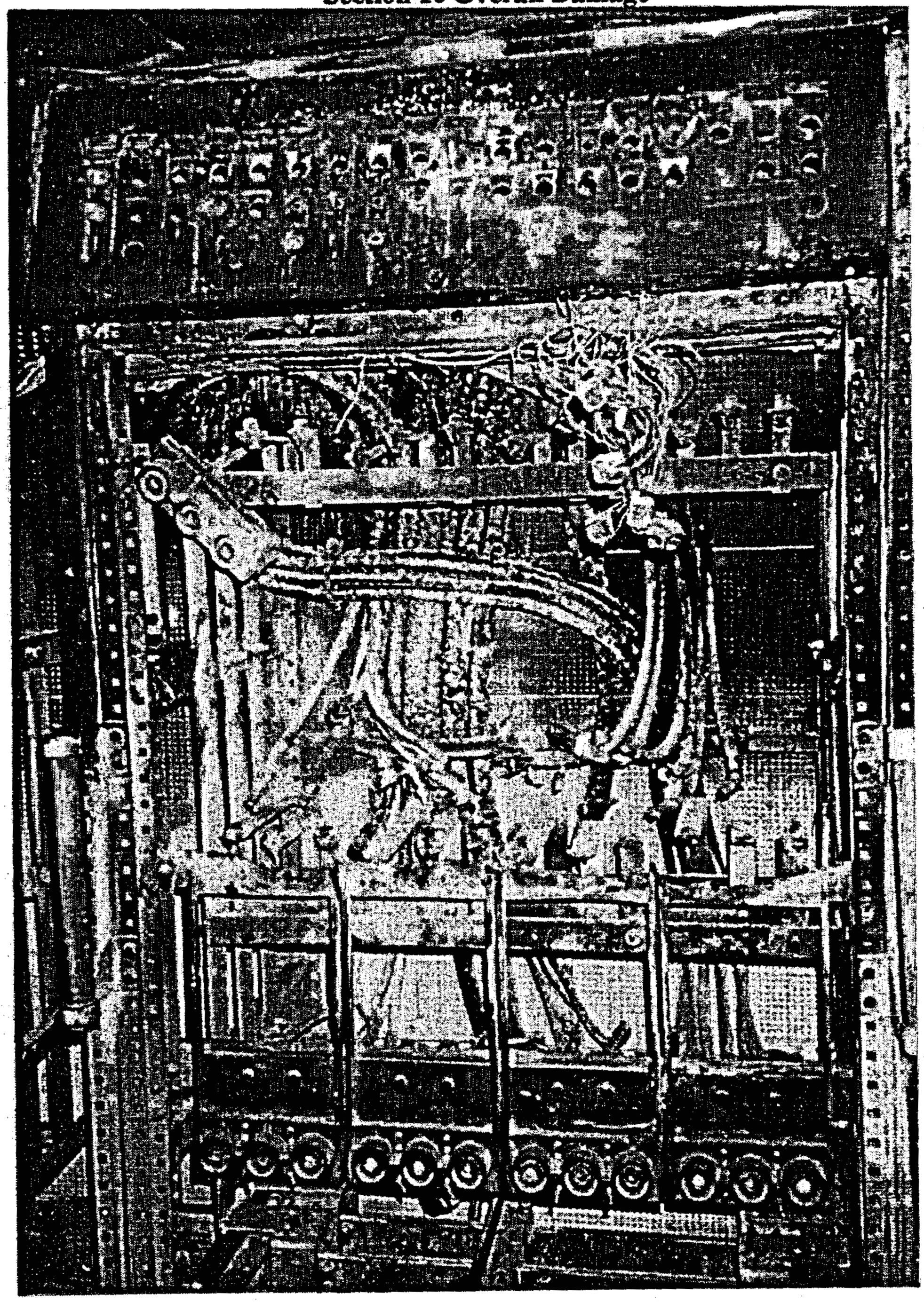
Attachment 4
Overhead Lighting Fixture



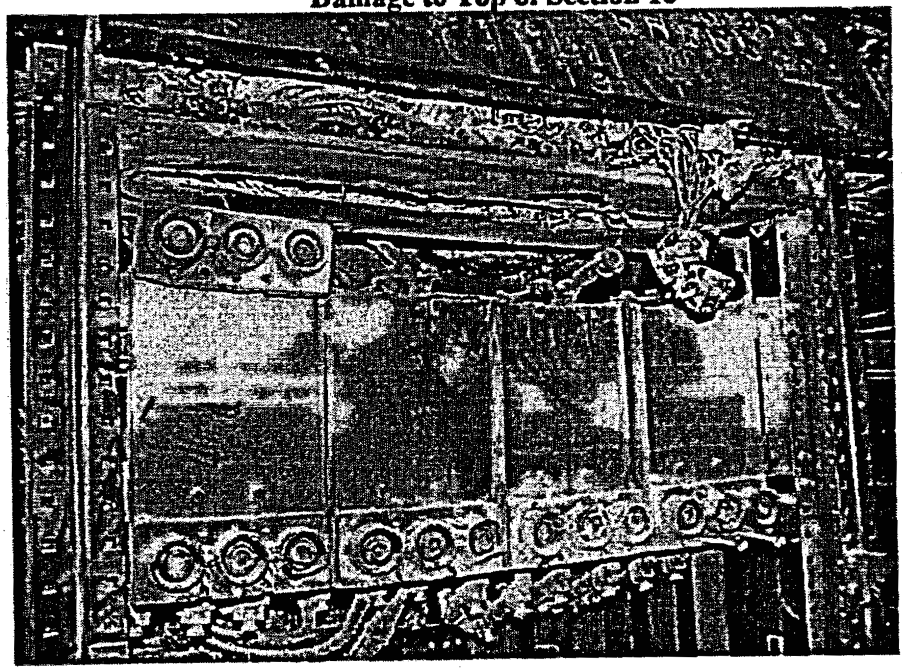
Attachment 5
Generator Breaker Contacts



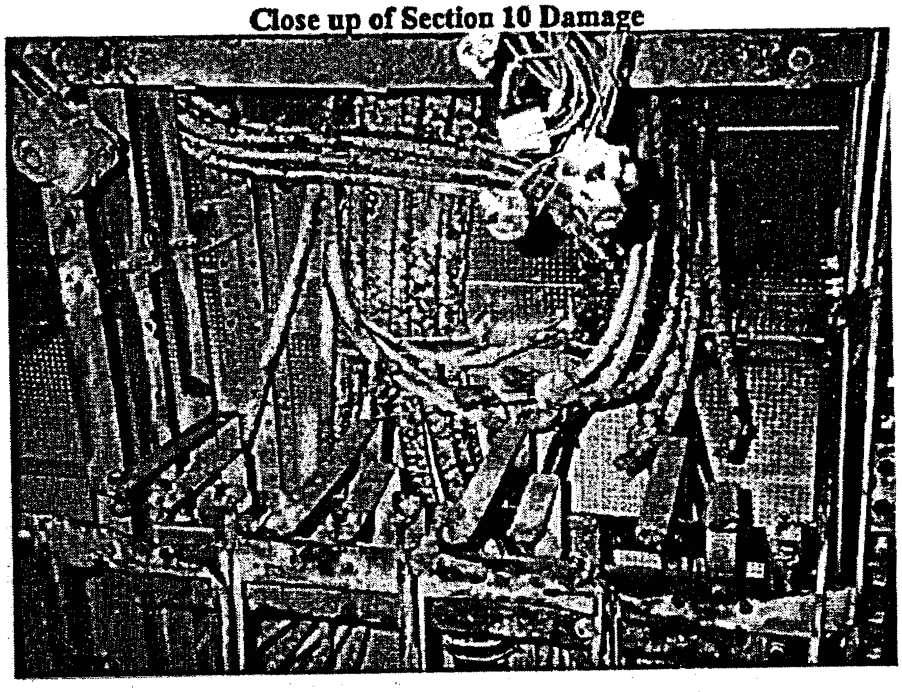
Attachment 6
Section 10 Overall Damage



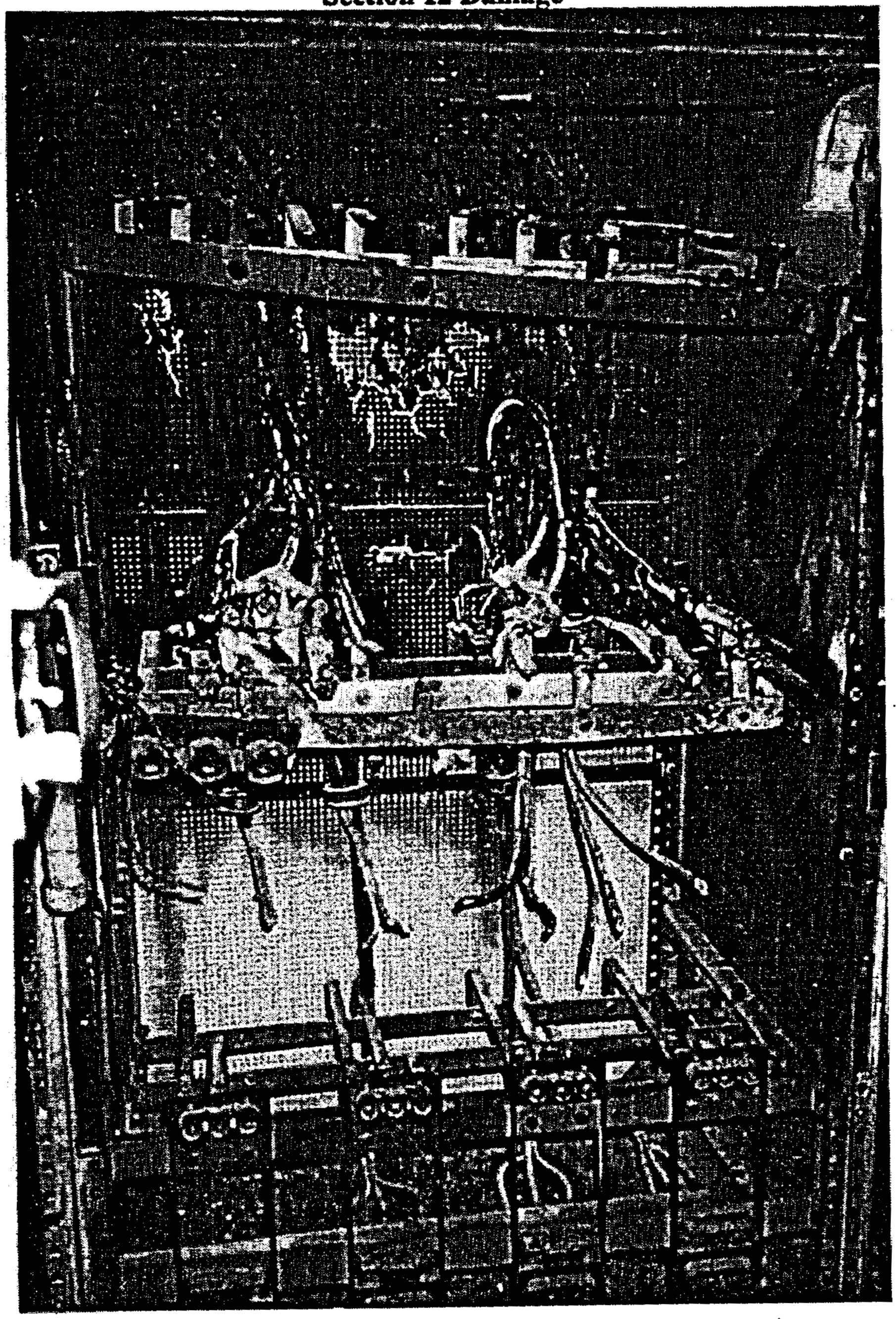
Attachment 7
Damage to Top of Section 10



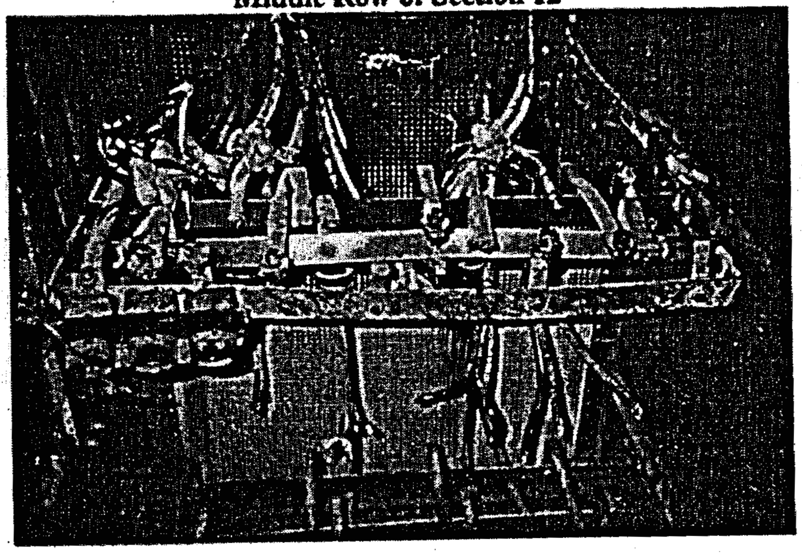
Attachment 8
Close up of Section 10 Damage



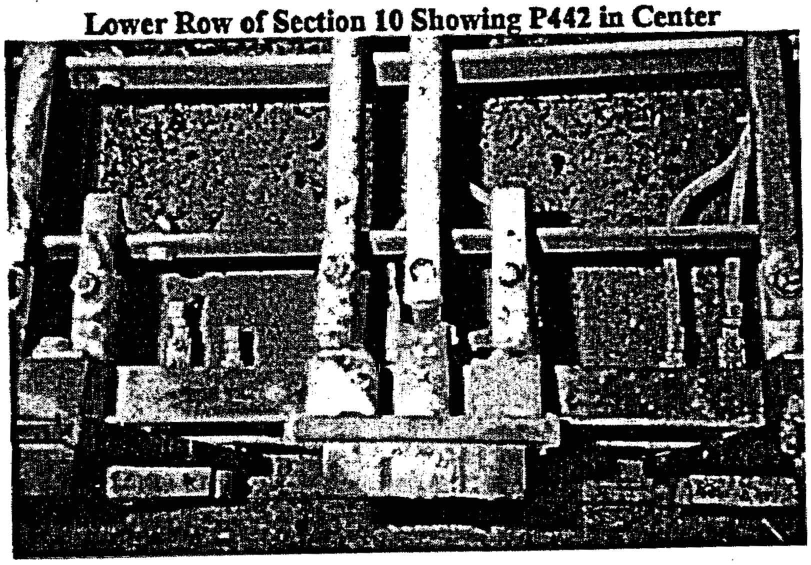
Attachment 9
Section 12 Damage



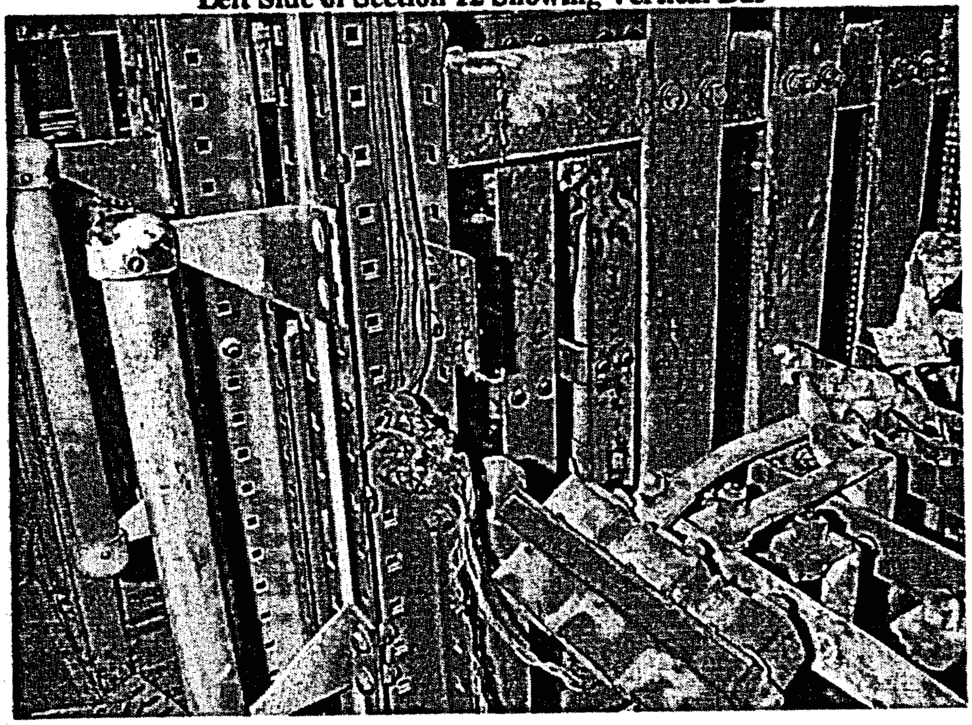
Attachment 10
Middle Row of Section 12



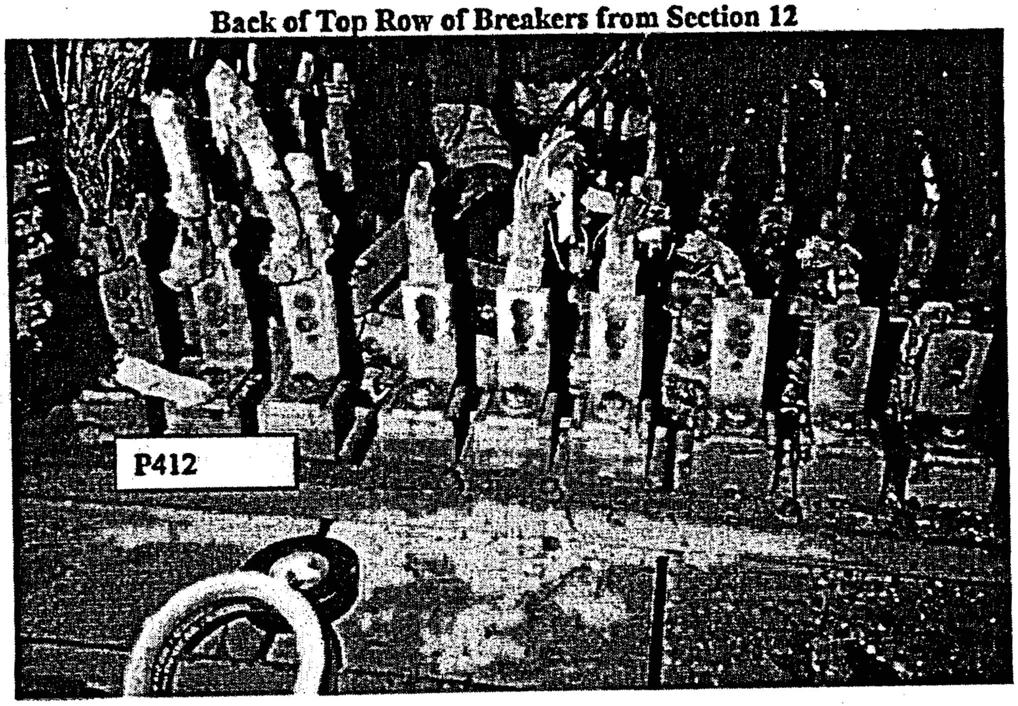
Attachment 11
Lower Row of Section 10 Showing P442 in Center



Attachment 12
Left Side of Section 12 Showing Vertical Bus

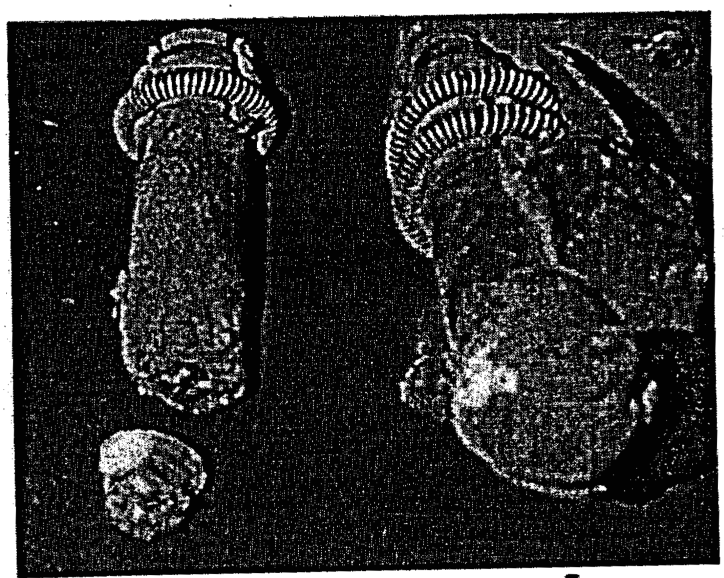


Attachment 13
Back of Top Row of Breakers from Section 12



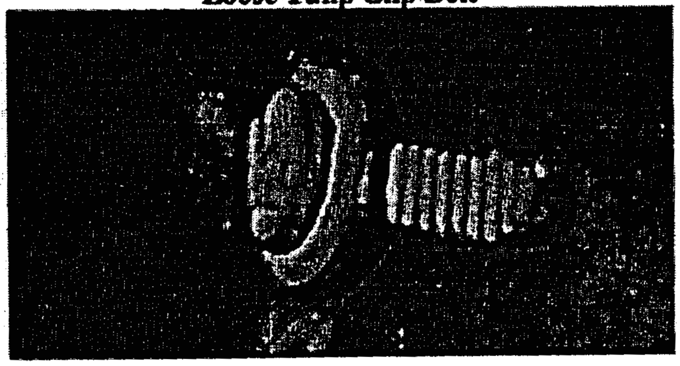
Attachment 14
Tulip Clip and Their Bolts

Clips 1 2 3 4 5



Clips 6 7

Attachment 15
Loose Tulip Clip Bolt



Attachment 16
Loose Cable in Section 12